Effects of Reaction Control System on Aerodynamics and Aerothermodynamics of Mars Entry Vehicles

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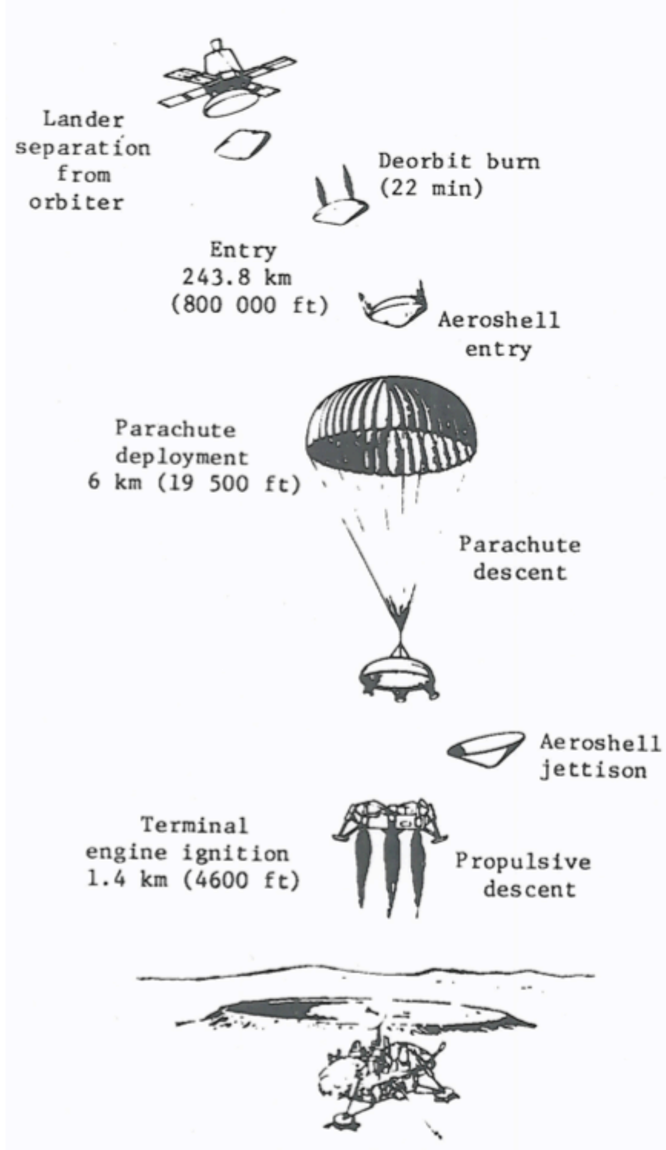
Introduction

- Past Mars missions landed within 100s of km from designated target
  - Unguided lifting (Viking 1, 2)
  - Unguided ballistic (Pathfinder, MER)
- New generation of Mars landers to deliver massive payloads to within 10s of km from target
  - Requires lifting actively guided entry with relartively high L/D (eg. MSL)
- Guided entry requires reaction control system (RCS)
  - Active control of direction of the lift vector
  - Rate damping
- Guidance maneuvers take advantage of dynamic pressure, so they take place in hypersonic and supersonic segments of the entry
  - Effect of RCS on aerothermal environment can be significant, impact TPS
  - RCS interference in aerodynamic characteristics neds to be understood to reliably predict flight



RCS/Gasdynamic Interaction Heritage

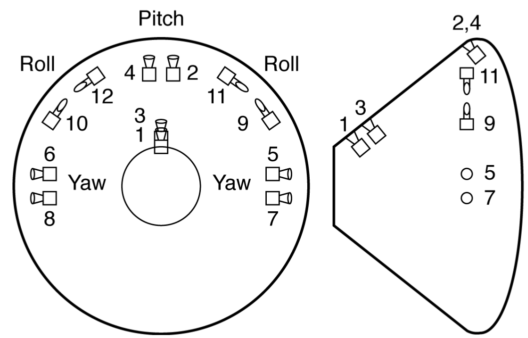
Apollo

- Entry Vehicle Control, NASA SP-8028, November 1969.
  - Apollo 7 reentry: “considerable pitch and yaw control activity in the transonic region during the final 2 min before drogue deployment“, from simulation they concluded that this was a result of thruster jet interaction with flow around the vehicle and strong winds.
- NASA TM-X-1063
  - Mention of interference patterns on aftbody caused by RCS jets
- NASA TN-D-6028
  - Heating on the leeside of the spacecraft increased during RCS firings up to 5 times that measured between firings

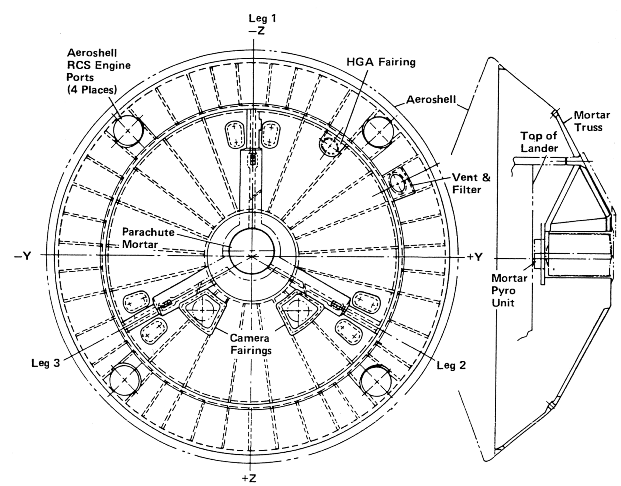
Viking

- Blake, W. W., Polutchko, R. J.,”Hypersonic Experimental Aerodynamic Characteristics of Viking Lander Capsule,” Martin Marietta Corporation, TR-3709012, May 8, 1970
  - Aero/RCS interaction estimated in wind tunnel tests at M=20 using solid bodies to represent thruster plumes
  - The data were inconclusive due to insufficient accuracy of the low AOA data
  - The recommendation was use a balance designed to measure small C_N and C_m, and large C_A to minimize data uncertainties, but this apparently was never accomplished for Viking

Apollo



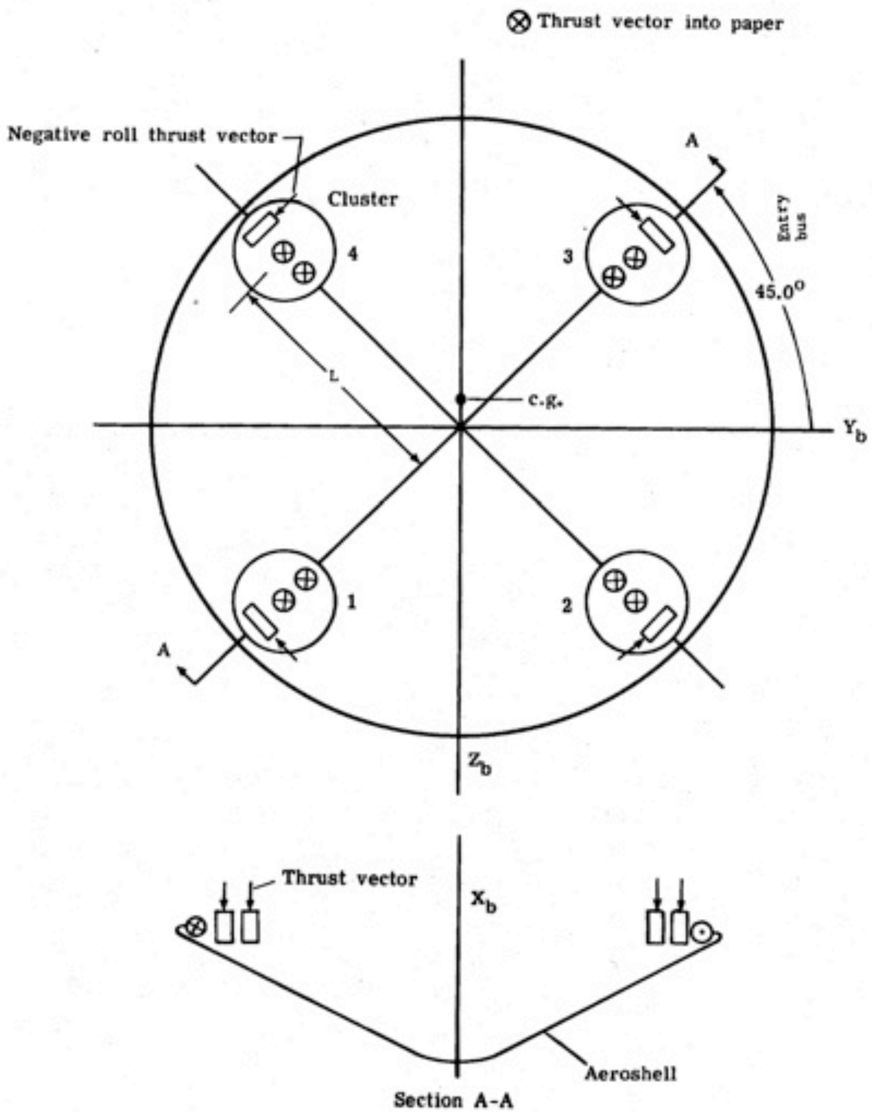
Attitude Command	Reaction Jets Fired
Pitch down	2 and 4
Pitch up	1 and 3
Yaw right	6 and 8
Yaw left	5 and 7
Roll left	10 and 11
Roll right	9 and 12



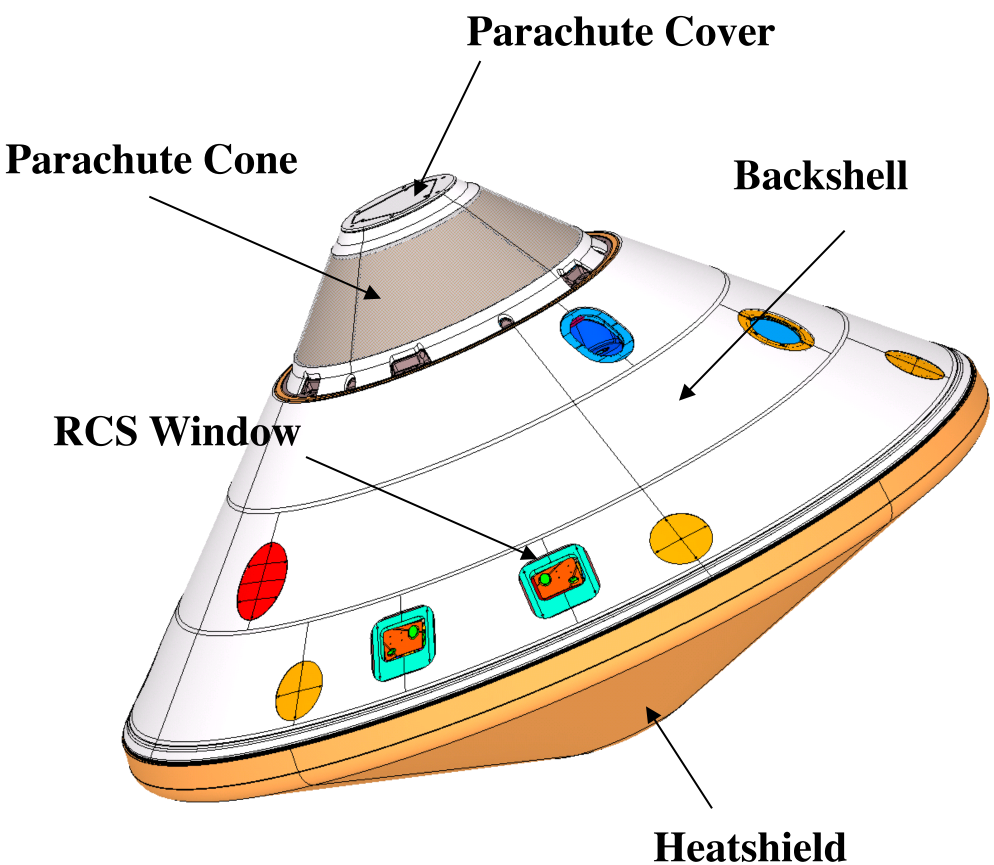
Viking

Reaction Control Systems

Viking Lander RCS

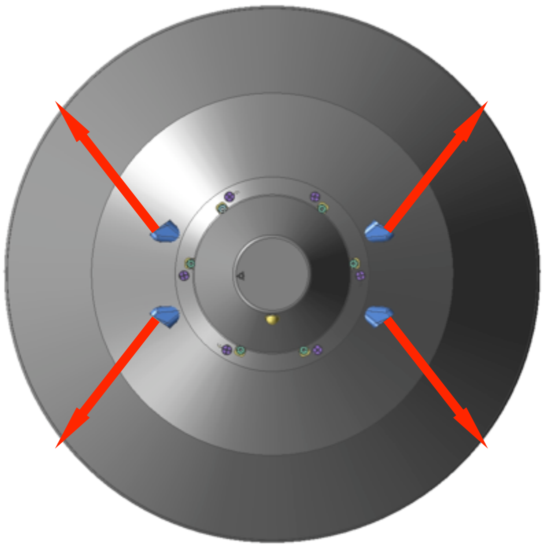


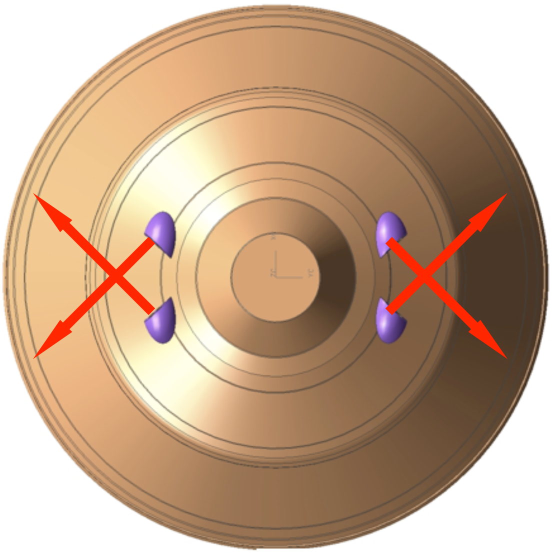
MPL/Phoenix RCS

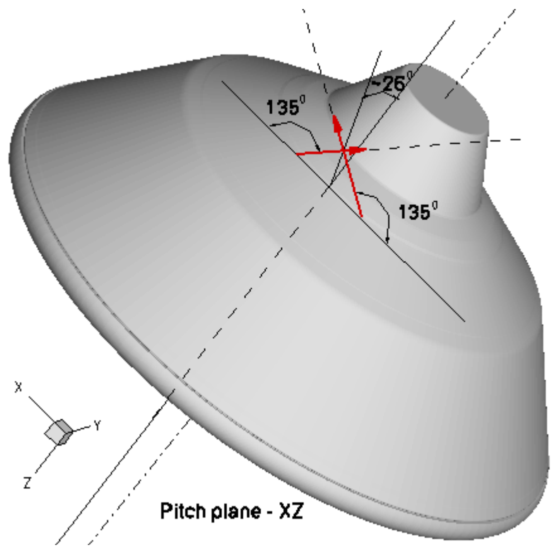


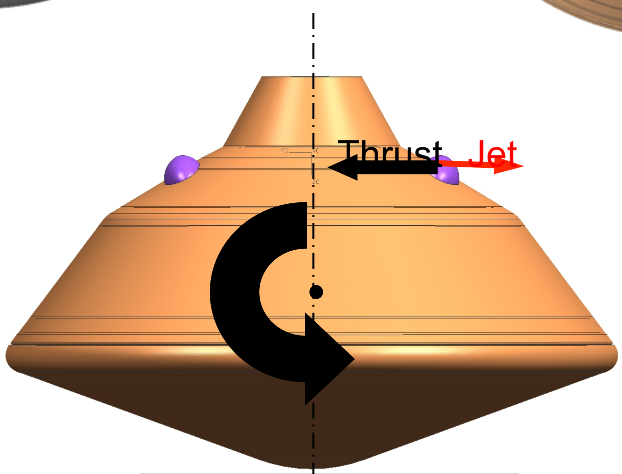
Reaction Control Systems (cont.)

Candidate MSL RCS

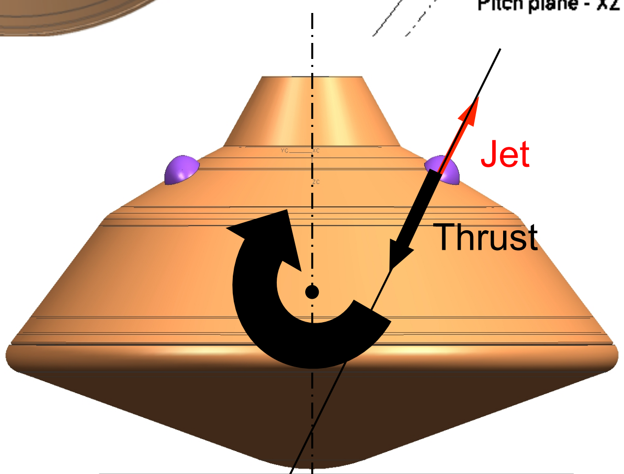






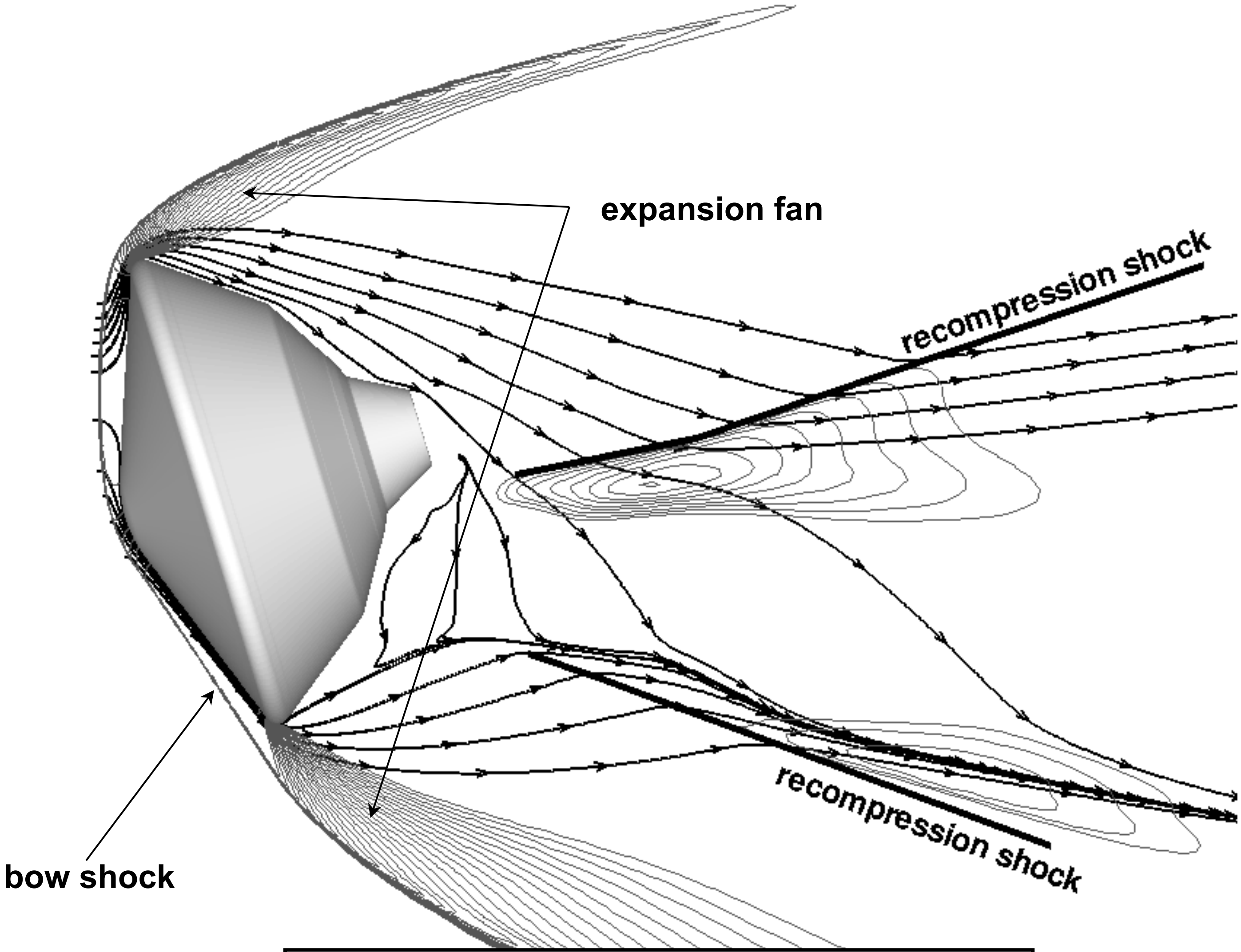


Thust Aft of CG



Thrust Ahead of CG

Near-capsule flowfield



Flow around MSL Capsule at Mach 18.1

Jet-Wake Interaction

- Interaction of an underexpanded jet with crossflow extensively studied
  - Applicability of existing analyses to scientific planetary entry vehicles is limited
  - Massively separated wake, jet is penetrating flows of changing character
- Analyses and results are configuration specific
  - Interaction with attached vs. separated flow, local flow conditions
  - Pointing of the jet, location on the aftshell

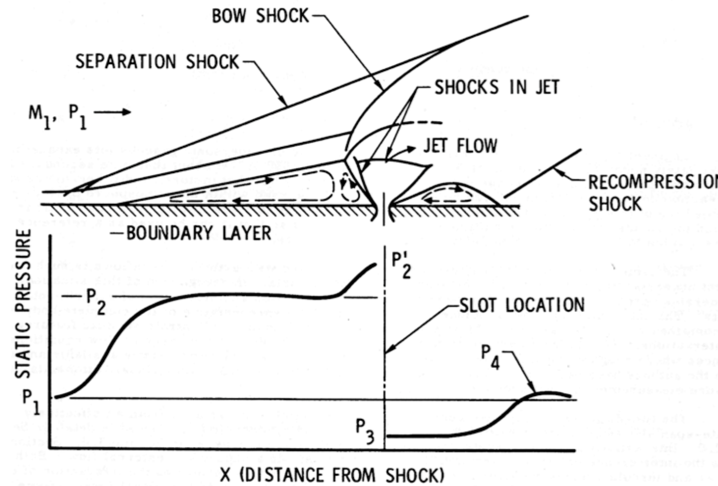
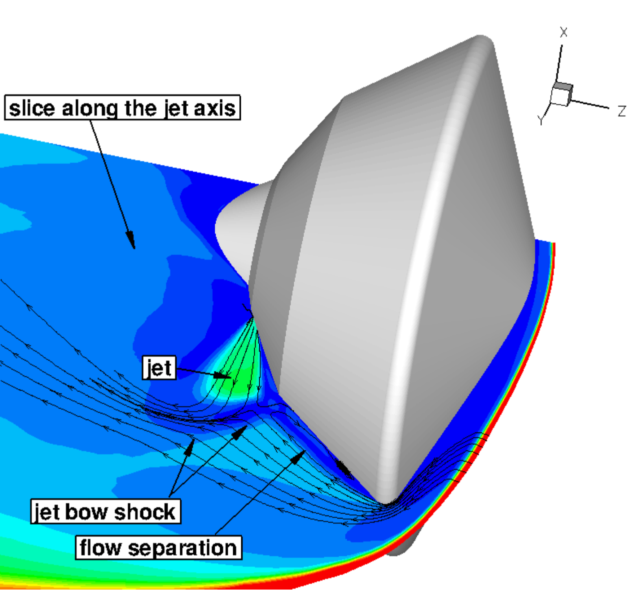
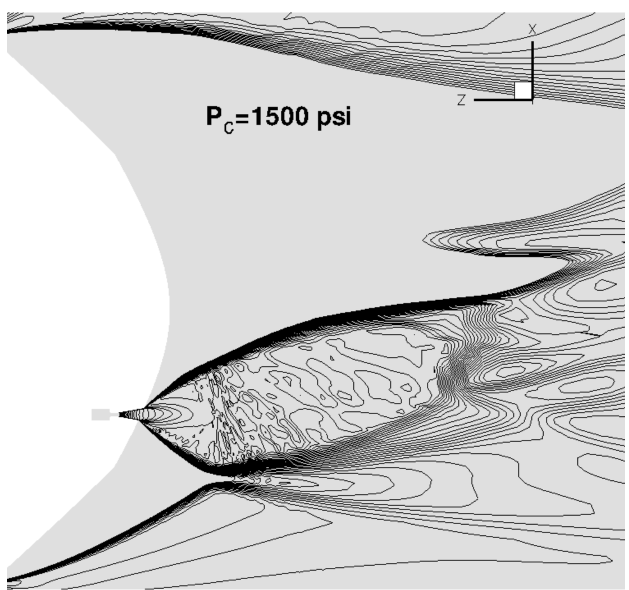


Image from AGARD No. 137

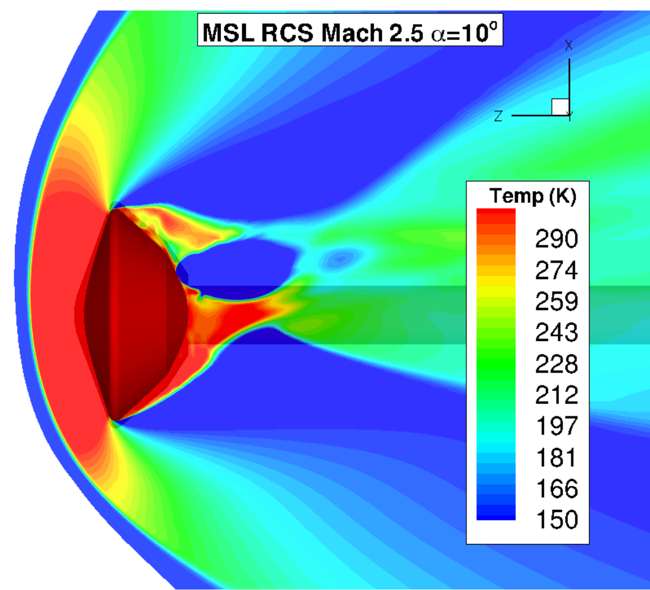
Interaction with attached flow



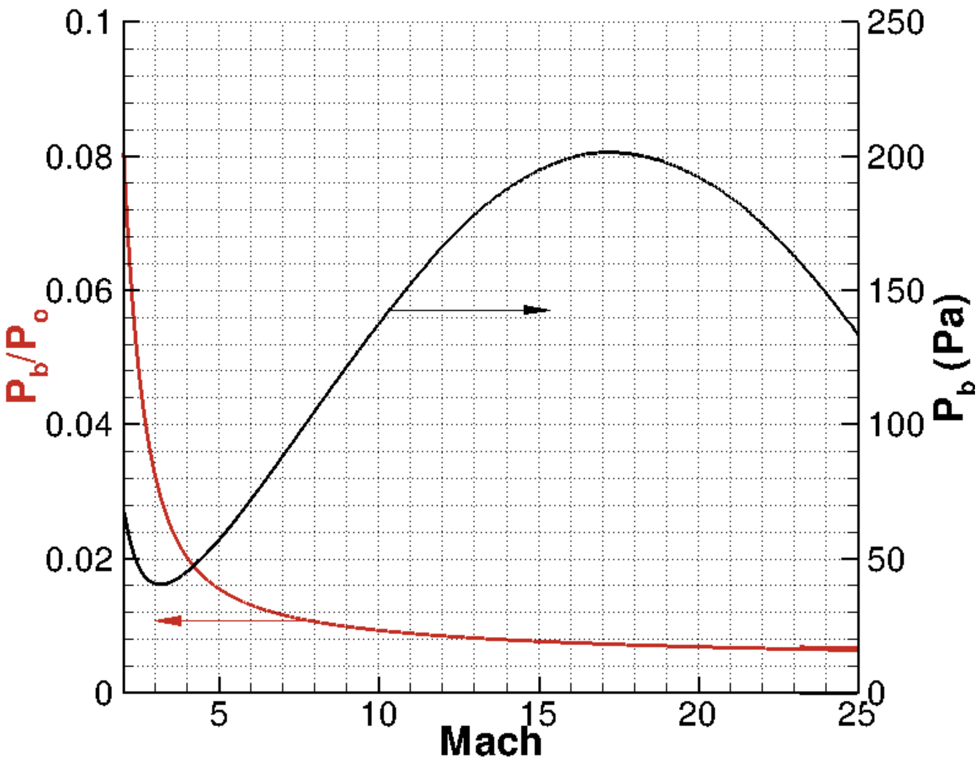
Interaction with shear layer

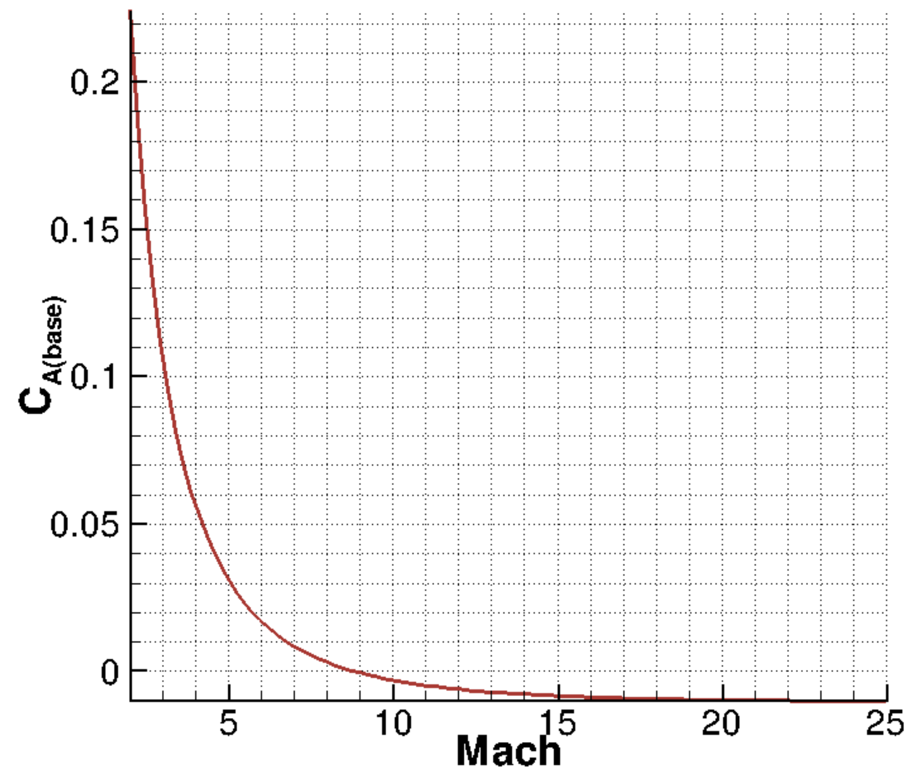


Interaction with separated flow



Aftbody Aerodynamics



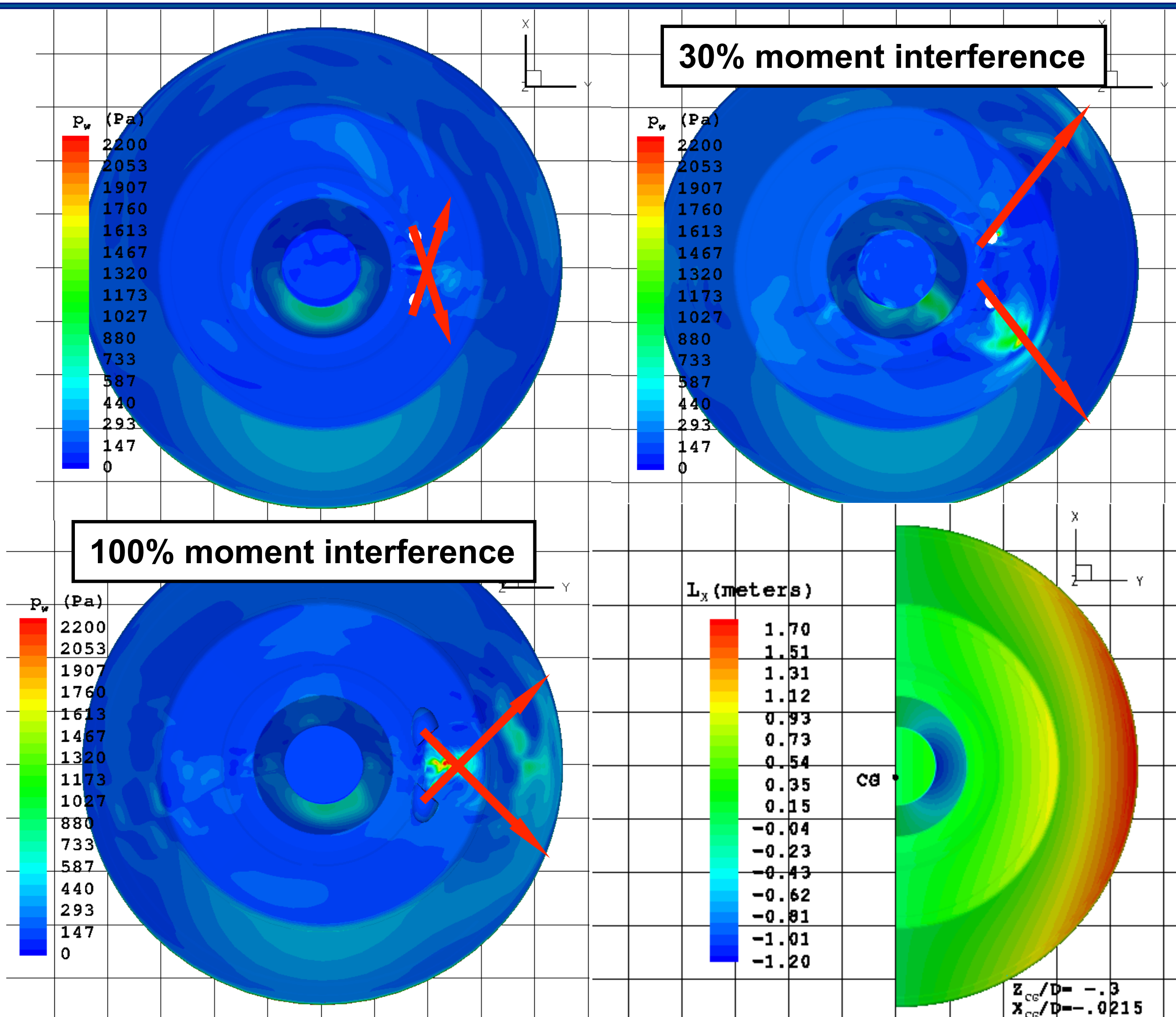


Viking-derived base correction:

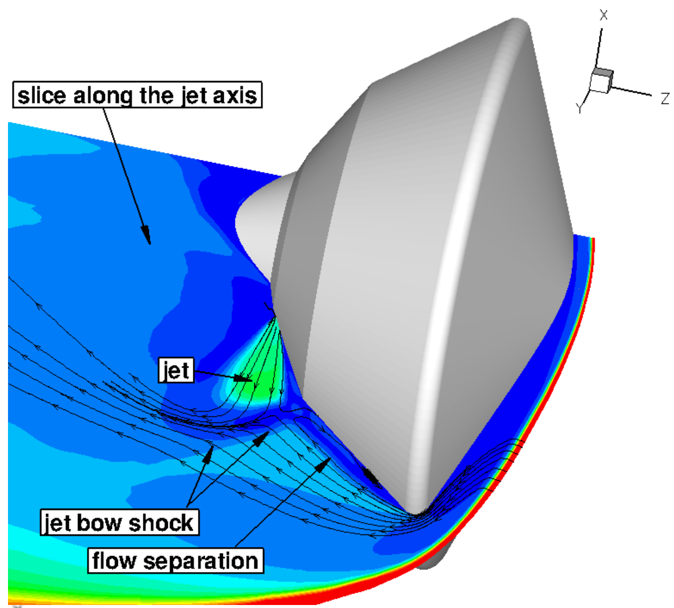
$$C_{A(base)} = C_{p,b} = a_0 + \frac{a_1}{M_\infty} + \frac{a_2}{M_\infty^2} + \frac{a_3}{M_\infty^3}$$

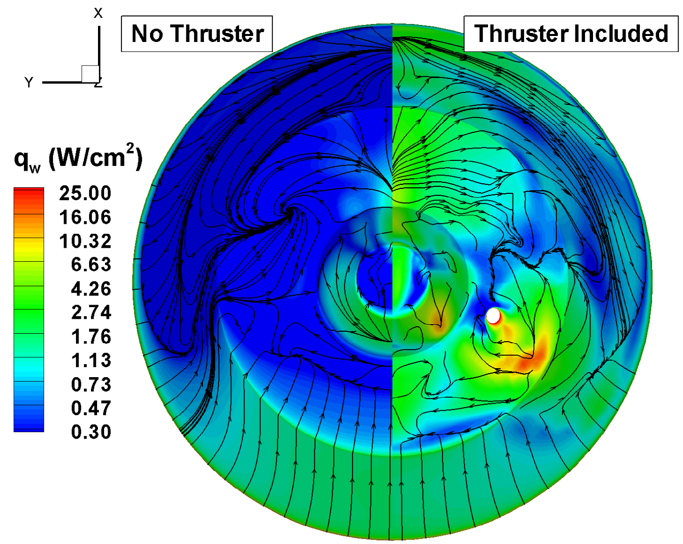
a_0 = 8.325E-03
a_1 = 1.129E-01
a_2 = -1.801E+00
a_3 = 1.289E+00

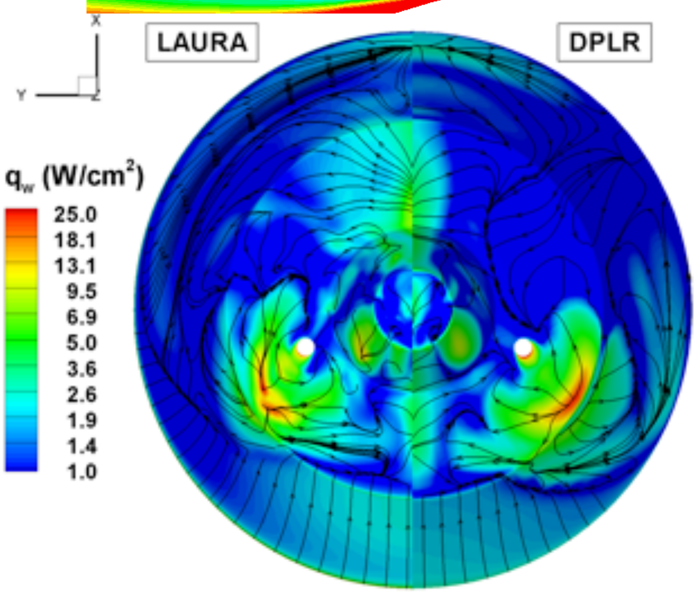
Aerodynamic Effects

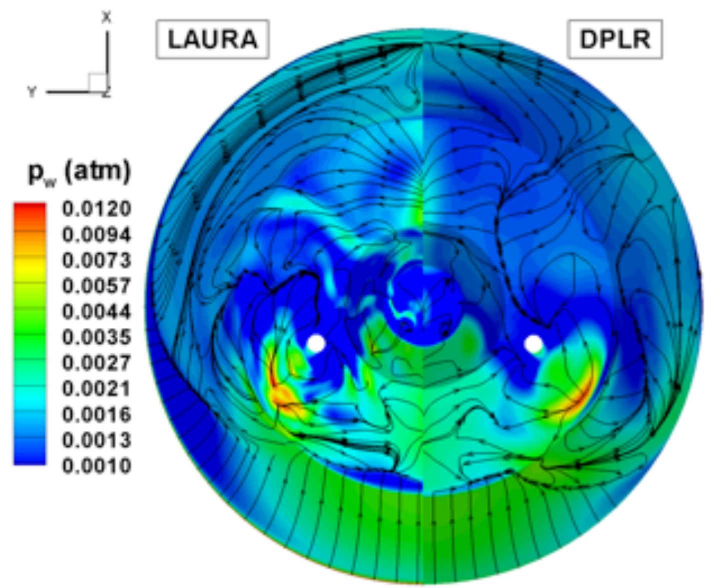


Aerothermal Effects



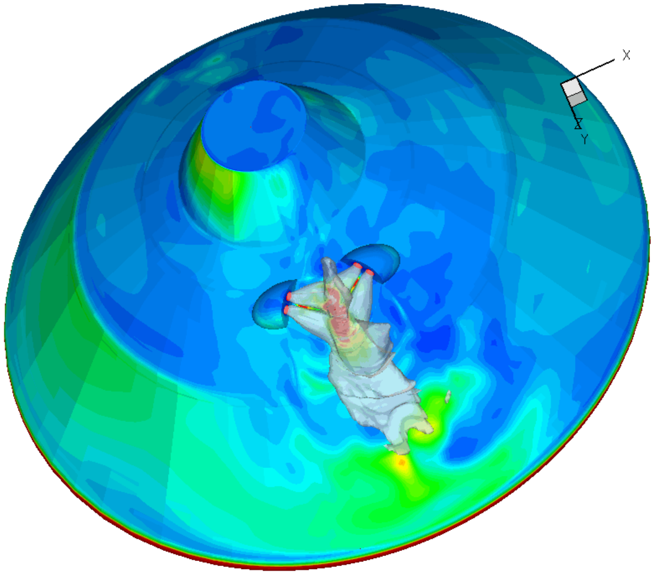


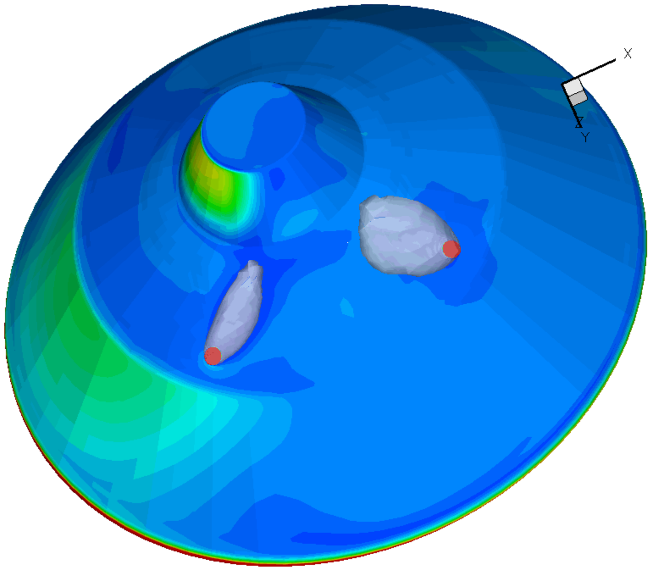




Summary

- RCS interference with aerodynamics
  - Changes in aerodynamics occur in both supersonic and hypersonic segments of the entry trajectory
    - Control gain and aerodynamic cross coupling can occur
    - In some cases the authority of RCS can be overwhelmed by the induced aerodynamic moments
  - Computational and experimental analyses help bound the phenomena
    - Extensive experimental program to validate CFD computations
    - Supersonic and hypersonic regimes
    - Computation using LAURA, DPLR, FUN3D, US3D
  - Difficulties in both computational methods and experiment
    - Maturety of computational tools
    - Small interference moments in comparisson to the overall capsule moments
- Impact of RCS on aerothermal evironments
  - Aeroheating increase by as much as an order of magnitude depending on the specifics of the jet interaction
  - Impact on TPS selection, cost, schedule
- Based on analyses performed to date paradigms have been developed to minimize destructive interference of RCS jets

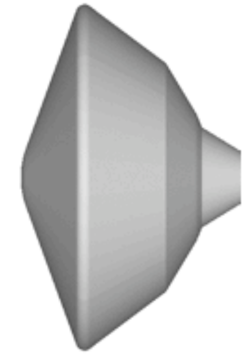




BACKUP

EDL Systems

Table 1. Comparison of Mars Entry Capsules

	Viking 1/2	Pathfinder	MER A/B	Phoenix	MSL
					
Diameter, m	3.5	2.65	2.65	2.65	4.5
Entry Mass, kg	930	585	840	602	2919
Landed Mass, kg	603	360	539	364	1541
Landing Altitude, km	-3.5	-1.5	-1.3	-3.5	+1.0
Landing Ellipse, km	420 x 200	100 x 50	80 x 20	75 x 20	< 10 x 10
Relative Entry Vel., km/s	4.5/4.42	7.6	5.5	5.9	> 5.5
Relative Entry FPA, deg	-17.6	-13.8	-11.5	-13	-15.2
$m/(C_DA)$, kg/m^2	63.7	62.3	89.8	65	126
Turbulent at Peak Heating?	No	No	No	No	Yes
Peak Heat Flux, W/cm^2	24	115	54	56	243
Hypersonic α, deg	-11.2	0	0	0	-15.5
Hypersonic L/D	0.18	0	0	0	0.24
Control	3-axis	Spinning	Spinning	3-axis	3-axis
Guidance	No	No	No	No	Yes

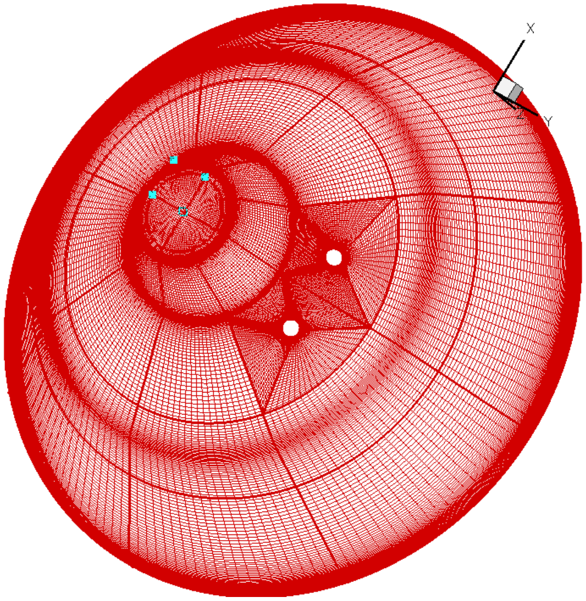
Ideal Authority

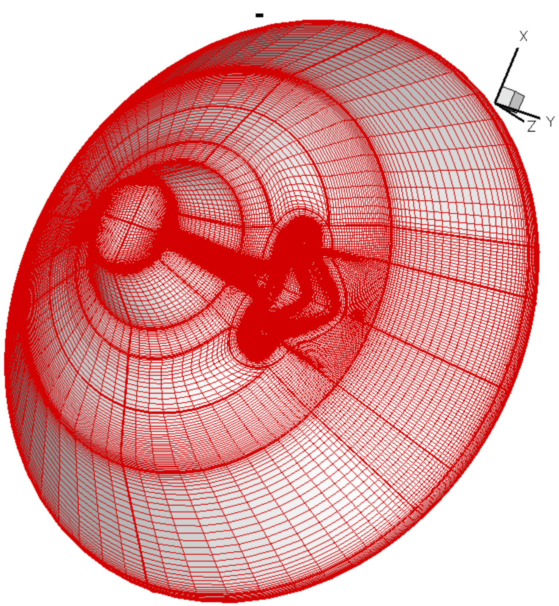
Table 2. Comparison of ideal authority of Viking, MPL/Phoenix and MSL

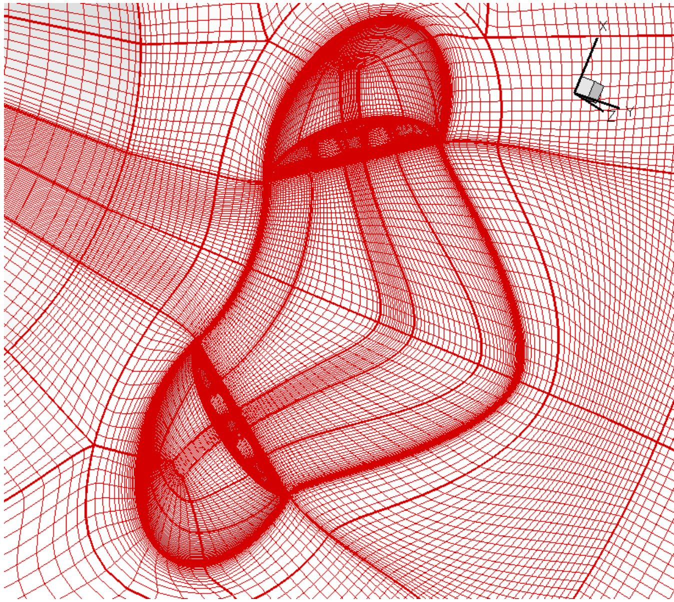
	N-m			Kg-m^2			deg/sec^2		
	M_X	M_Y	M_Z	I_{XX}	I_{YY}	I_{ZZ}	α_X	α_Y	α_Z
Viking 1, 2	152.7	146/-159.4	108	536	423	786	16.3	19.8/-21.6	7.9
MPL/Phoenix	10.7	58.07	10.06	192	189	286	3.2	17.6	2
MSL	675.4	980.7/-1160	705	3055	3952	4836	12.7	14.2/-16.8	8.4

Algorithm/Grids

- Calculations in LAURA using 8-species Mars gas + ammonia as propellant
- Calculations in DPLR using 8-species Mars gas + ammonia as propellant or byproducts of hydrozene combustion (N2, H2, NH3)
- Grids
  - Detailed fine grids contain up to 60M nodes
    - Created by Victor Lessard, extends to engine chambers
  - Prelimminary grids
    - created using RTF MORPH tool and don't reflect any internal flow
- Solutions are computed at Mach 18.1, q=15.9 kPa

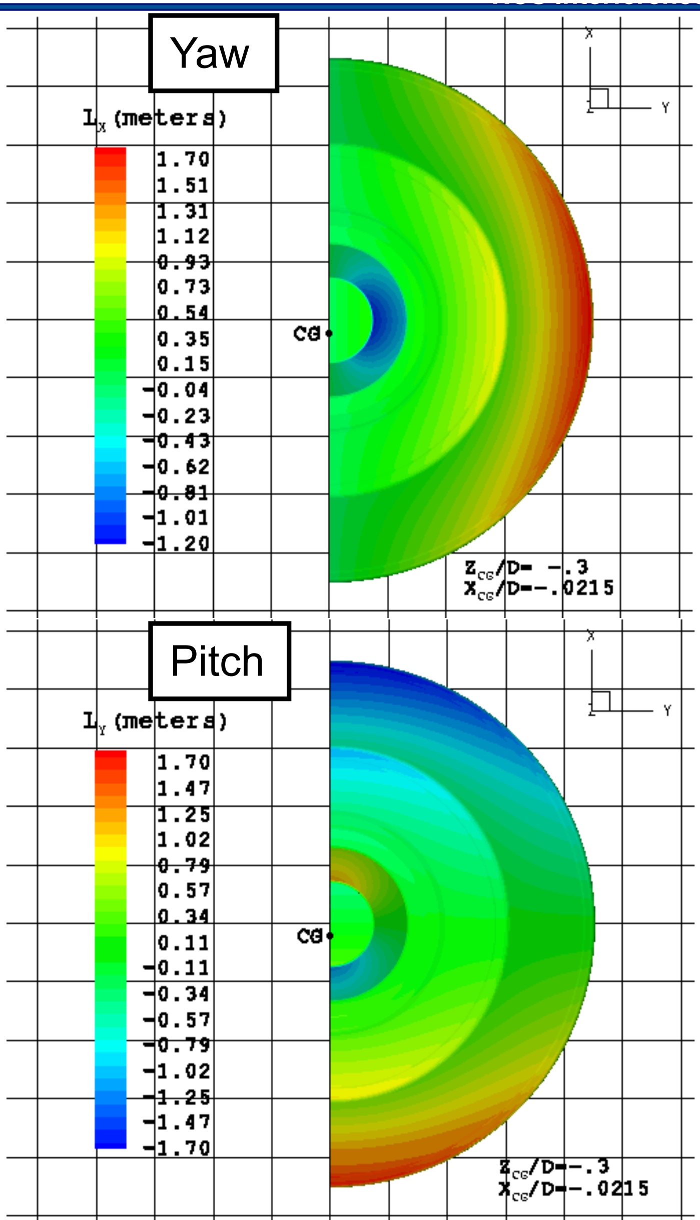




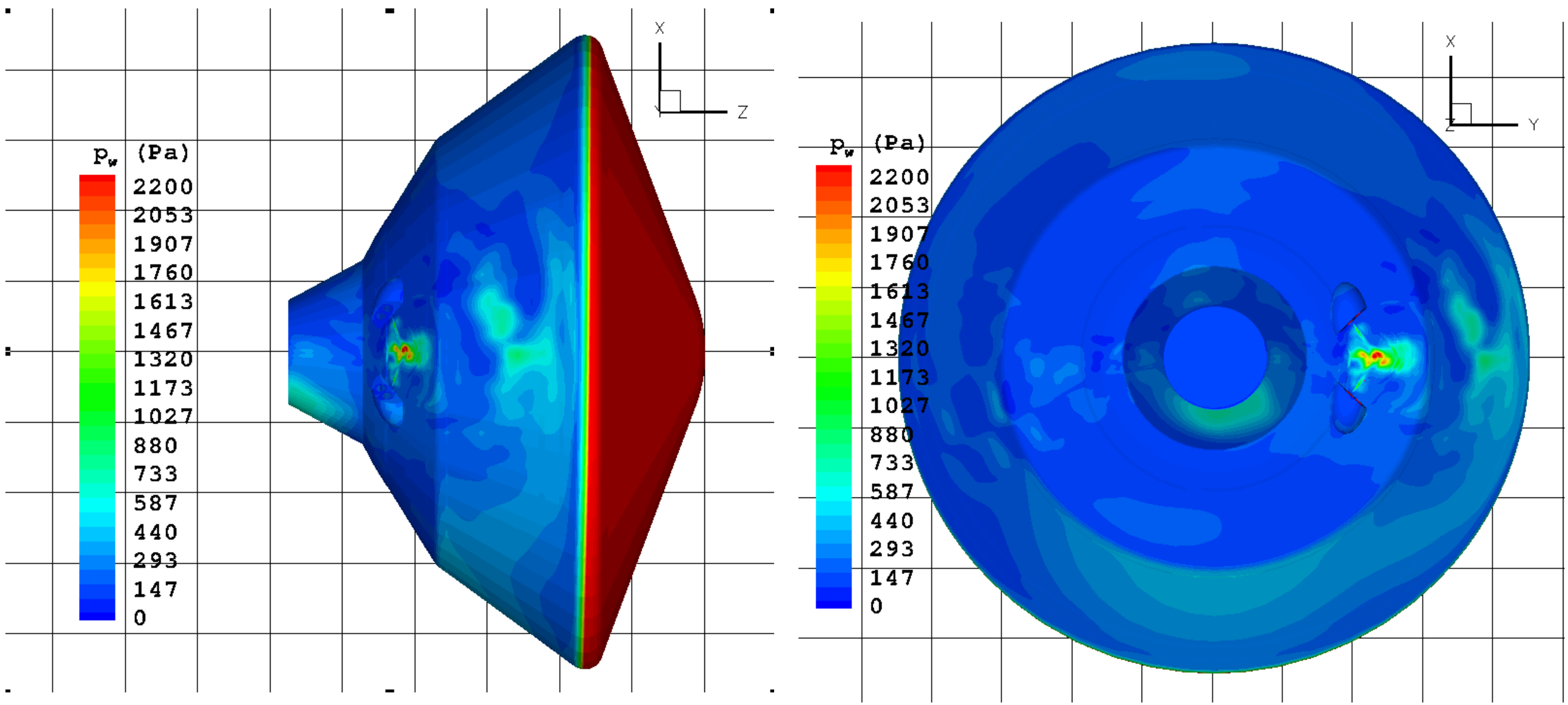


Geometric Considerations

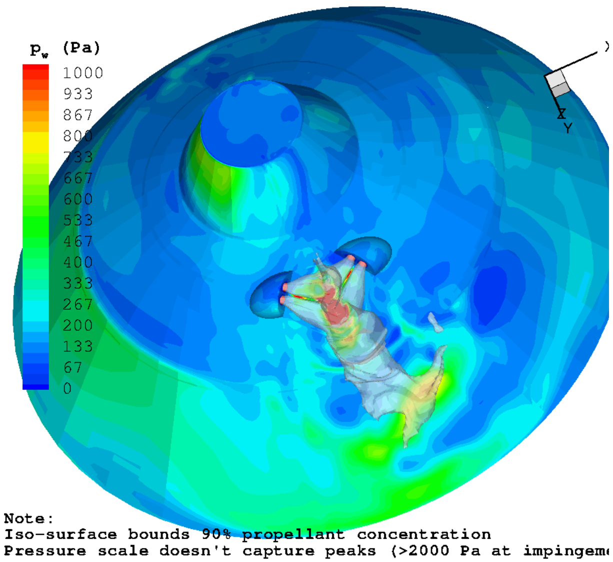
- Same amount of pressure applied to different locations on the backshell wil produce different moments about the CG
- Moment arms (L_X, L_Y), computed from a surface-normal through a point and the location of the CG illustrate the regions of high sensitivity of capsule moments to changes in surface pressure
  - In yaw, capsule moments are very sensitive to change in pressure on the far side, and on the parachute closeout cone
  - In pitch, capsule moments are very sensitive to changes in wind/lee shoulder regions; the parachute closeout cone can also generate significant torques if shocks/plumes impinge on it

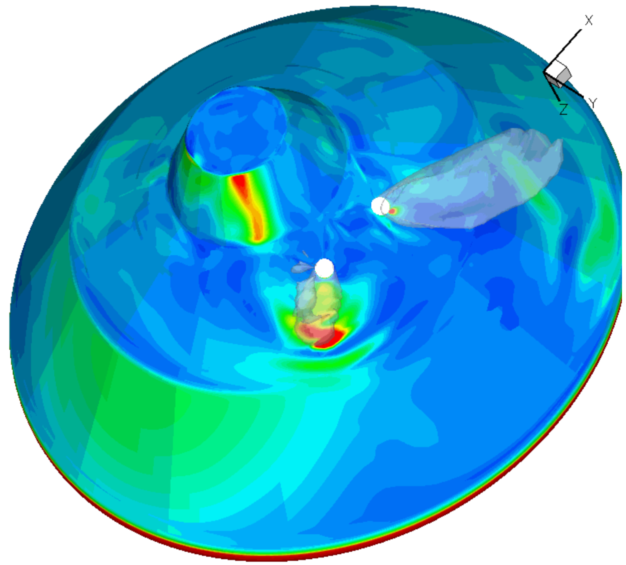


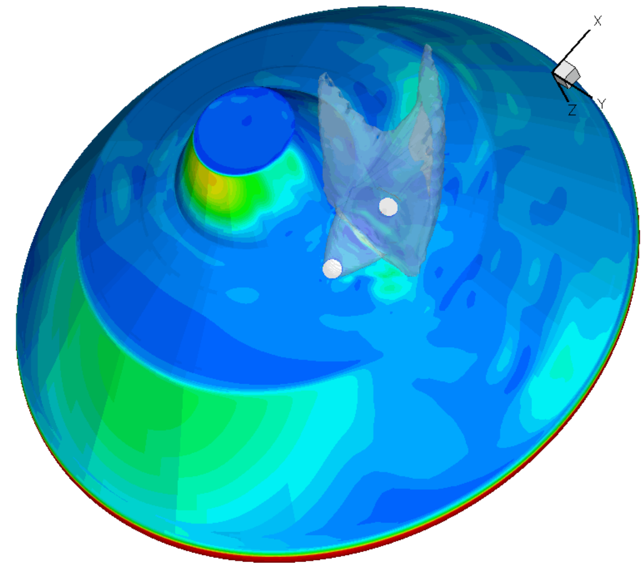
Aerodynamic Effects (II)



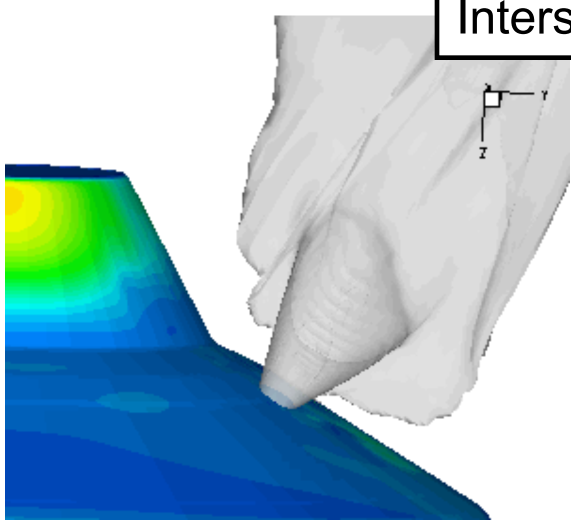
RCS Plumes of Candidate MSL RCS

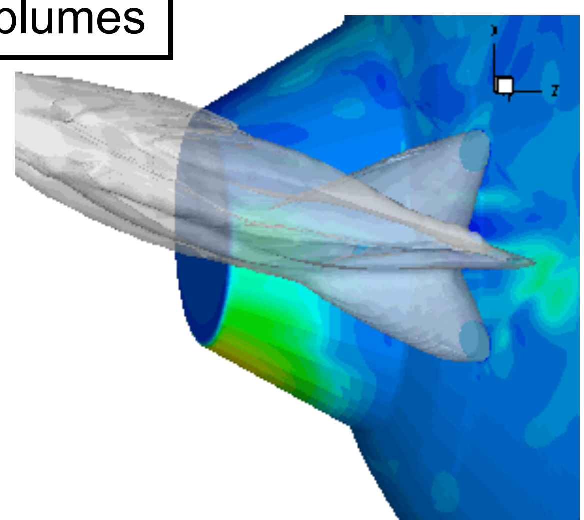






Intersecting plumes





Backshell Heating